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Observation of Time-Dependent CP Violation in $B^0 \to \eta' K^0$ Decays and Improved Measurements of CP Asymmetries in $B^0 \to \phi K^0$, $K_S^0 K_S^0 K_S^0$ and $B^0 \to J/\psi K^0$ Decays

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We present improved measurements of CP-violation parameters in $B^0 \to \phi K^0$, $\eta' K^0$, $K_S^0 K_S^0 K_S^0$ decays based on a sample of 535×10^6 $B\overline{B}$ pairs collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB energy-asymmetric e^+e^- collider. We obtain $\sin 2\phi_1^{\rm eff} = +0.64 \pm 0.10({\rm stat}) \pm 0.04({\rm syst})$ for $B^0 \to \eta' K^0$, $+0.50 \pm 0.21({\rm stat}) \pm 0.06({\rm syst})$ for $B^0 \to \phi K^0$, and $+0.30 \pm 0.32({\rm stat}) \pm 0.08({\rm syst})$ for $B^0 \to K_S^0 K_S^0 K_S^0$ decays. We have observed CP violation in the $B^0 \to \eta' K^0$ decay with a significance of 5.6 standard deviations. We also perform an improved measurement of CP asymmetries in $B^0 \to J/\psi K^0$ decays and obtain $\sin 2\phi_1 = +0.642 \pm 0.031({\rm stat}) \pm 0.017({\rm syst})$.

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Particles from physics beyond the standard model (SM) may contribute to B^0 meson decays mediated by flavor-changing $b \to s$ transitions via additional quantum loop diagrams, and potentially induce large deviations from the SM expectation for time-dependent CP asymmetries [1]. In the decay chain $\Upsilon(4S) \to B^0\overline{B}{}^0 \to f_{CP} f_{\rm tag}$, where one of the B mesons decays at time t_{CP} to a CP eigenstate f_{CP} and the other decays at time $t_{\rm tag}$ to a final state $f_{\rm tag}$ that distinguishes between B^0 and $\overline{B}{}^0$, the decay rate has a time dependence [2] given by

$$\mathcal{P}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \Big\{ 1 \ + \ q \cdot \Big[\mathcal{S}_f \sin(\Delta m_d \Delta t) + \ \mathcal{A}_f \cos(\Delta m_d \Delta t) \Big] \Big\}. \quad (1)$$

Here $\mathcal{S}_f$ and $\mathcal{A}_f$ are CP-violation parameters, τ_{B^0} is the B^0 lifetime, Δm_d is the mass difference between the two B^0 mass eigenstates, $\Delta t = t_{CP} - t_{\rm tag}$, and the b-flavor charge $q = +1$ (-1) when the tagging B meson is a B^0 ($\overline{B}{}^0$). In the SM, CP violation arises only from the irreducible Kobayashi-Maskawa phase [3] in the weak-interaction quark-mixing matrix [4]. The SM approximately predicts $\mathcal{S}_f = -\xi_f \sin 2\phi_1$[5] and $\mathcal{A}_f = 0$ for both $b \to c\bar{c}s$ and $b \to s\bar{q}q$ transitions, where $\xi_f = +1$ (-1) corresponds to CP-even (-odd) final states, in the leading order. Recent SM calculations [6] for the effective $\sin 2\phi_1$ values, $\sin 2\phi_1^{\rm eff}$, obtained from $B^0 \to \phi K^0$, $\eta' K^0$ and $K_S^0 K_S^0 K_S^0$ agree with $\sin 2\phi_1$, as measured in $B^0 \to J/\psi K^0$ decays, at the level of 0.01. Thus comparison of measurements of $\mathcal{S}_f$ and $\mathcal{A}_f$ between modes is an important test of the SM.

Previous measurements of CP asymmetries in $b \to s\bar{q}q$ transitions by Belle [7] and BaBar [8] differed from the SM expectation, although the deviation was not statistically significant. BaBar has since updated their results [9]. In this Letter we describe improved measurements of $\mathcal{S}_f$ and $\mathcal{A}_f$ in $B^0 \to \phi K_S^0$, ϕK_L^0, $\eta' K_S^0$ and $K_S^0 K_S^0 K_S^0$ decays using a data sample of 492 fb^{-1} (535×10^6 $B\overline{B}$ pairs), which is nearly twice that used for our previous measurements. The analysis has also been improved by the addition of the following decay chains: $B^0 \to \phi K_S^0$, $\phi \to K_S^0 K_L^0$; $B^0 \to \eta' K_L^0$; $B^0 \to \eta' K_S^0$, $K_S^0 \to \pi^0\pi^0$. We also describe improved measurements of $\sin 2\phi_1$ and $\mathcal{A}_f$ in $B^0 \to J/\psi K_S^0$ and $J/\psi K_L^0$ decays

using the same data sample; our previous measurement used a 140 fb^{-1} data sample [10]. These modes have the largest statistics coupled with the smallest theoretical uncertainties and thus provide a firm reference point for the SM.

At the KEKB energy-asymmetric e^+e^- (3.5 GeV on 8.0 GeV) collider [11], the $\Upsilon(4S)$ is produced with a Lorentz boost of $\beta\gamma = 0.425$ nearly along the electron beamline (z). Since the B^0 and $\overline{B}^0$ mesons are approximately at rest in the $\Upsilon(4S)$ center-of-mass system (cms), Δt can be determined from the displacement in z between the f_{CP} and $f_{\rm tag}$ decay vertices: $\Delta t \simeq (z_{CP} - z_{\rm tag})/(\beta\gamma c) \equiv \Delta z/(\beta\gamma c)$.

The Belle detector [12] is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter comprised of CsI(Tl) crystals (ECL) located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to detect K_L^0 mesons and to identify muons (KLM).

Charged tracks reconstructed with the CDC, except for tracks from $K_S^0 \to \pi^+\pi^-$ decays, are required to originate from the interaction point (IP). We distinguish charged kaons from pions based on a kaon (pion) likelihood $\mathcal{L}_{K(\pi)}$ derived from the TOF, ACC, and dE/dx measurements in the CDC. Photons are identified as isolated ECL clusters that are not matched to any charged track. Candidate K_L^0 mesons are selected from ECL and/or KLM hit patterns that are consistent with the presence of a shower induced by a K_L^0 meson.

The intermediate meson states are reconstructed from the following decays: $\pi^0 \to \gamma\gamma$, $K_S^0 \to \pi^+\pi^-$ (denoted by K_S^{+-}) or $\pi^0\pi^0$ (denoted by K_S^{00}), $\eta \to \gamma\gamma$ or $\pi^+\pi^-\pi^0$, $\rho^0 \to \pi^+\pi^-$, $\eta' \to \rho^0\gamma$ or $\eta\pi^+\pi^-$, $\phi \to K^+K^-$ and $J/\psi \to \ell^+\ell^-$ ($\ell = \mu, e$). We use all combinations of the intermediate states with the exception of $\{\eta \to \pi^+\pi^-\pi^0, \eta' \to \rho\gamma, K_S^{00}\}$ candidates for $B^0 \to \{\eta' K_S^{00}, \eta' K_L^0, J/\psi K_S^0\}$ decays, respectively. The reconstruction and selection criteria for $B^0 \to f_{CP}$ decay candidates are almost the same as in our previous measurement [7, 13]. The K_L^0 and K_S^{00} candidates for $\eta' K^0$ are reconstructed with the same method as used for ϕK^0 [13]. We reconstruct the $B^0 \to K_S^0K_S^0K_S^0$ decay in the $K_S^{+-}K_S^{+-}K_S^{+-}$ or $K_S^{+-}K_S^{+-}K_S^{00}$ final states. In addition, $\phi \to K_S^{+-}K_L^0$ decays are used for the $B^0 \to \phi K_S^{+-}$ sample. We identify candidate $B^0 \to f_{CP}$ decays without a K_L^0 meson using the energy difference $\Delta E \equiv E_B^* - E_{\rm beam}^*$ and the beam-energy constrained mass $M_{\rm bc} \equiv \sqrt{(E_{\rm beam}^*)^2 - (p_B^*)^2}$, where $E_{\rm beam}^*$ is the beam energy, and E_B^* and p_B^* are the energy and momentum, respectively, of the reconstructed B candidate, all measured in the cms frame. The signal candidates are selected by requiring $M_{\rm bc} \in (5.27, 5.29)$ GeV/c^2 and a mode-dependent ΔE window. Only $M_{\rm bc}$ is used to identify the decay $B^0 \to \phi K_S^0$ followed by $\phi \to K_S^0K_L^0$. Other candidate $B^0 \to f_{CP}$ decays with a K_L^0 are selected by requiring $p_B^* \in (0.2, 0.45)$ GeV/c for $B^0 \to J/\psi K_L^0$ candidates and $p_B^* \in (0.2, 0.5)$ GeV/c for the others.

The dominant background for the $b \to s\overline{q}q$ signal comes from continuum events $e^+e^- \to q\overline{q}$ where $q = u, d, s, c$. To distinguish these topologically jet-like events from the spherical B decay signal events, we combine a set of variables [7] that characterize the event topology into a signal (background) likelihood variable $\mathcal{L}_{\rm sig}$ ($\mathcal{L}_{\rm bkg}$), and impose loose mode-dependent requirements on the likelihood ratio $\mathcal{R}_{\rm s/b} \equiv \mathcal{L}_{\rm sig}/(\mathcal{L}_{\rm sig} + \mathcal{L}_{\rm bkg})$.

The contributions from $B\overline{B}$ events to the background for $B^0 \to f_{CP}$ candidates with a K_L^0 are estimated with Monte Carlo (MC) simulated events. The small ($\sim 3\%$) $B\overline{B}$ combinatorial background in $B^0 \to \eta' K_S^0(\eta' \to \rho^0\gamma)$ is estimated using MC events. We reject $K_S^0K_S^0K_S^0$ candidates if one of the K_S^0 pairs has an invariant mass within $\pm 2\sigma$ of the χ_{c0} mass or $\pm 1\sigma$ of the D^0 mass, where σ is the $K_S^0K_S^0$ mass resolution. The fraction of $B^0 \to K^+K^-K_S^0$ and $B^0 \to f_0(980)K_S^0$ ($f_0(980) \to K^+K^-$) events in the $B^0 \to \phi K_S^0$ sample is estimated to be $2.75 \pm 0.14\%$ and zero within error, respectively, from the Dalitz plot for $B \to K^+K^-K$ candidates [14].

The b-flavor of the accompanying B meson is identified from inclusive properties of particles that are not associated with the reconstructed $B^0 \to f_{CP}$ decay. The tagging information is represented by two parameters, the b-flavor charge q and r [15]. The parameter r is an event-by-event, MC-determined flavor-tagging dilution factor that ranges from $r = 0$ for no flavor discrimination to $r = 1$ for unambiguous flavor assignment. For events with $r > 0.1$, the wrong tag fractions for six r intervals, w_l ($l = 1, 6$), and their differences between B^0 and $\overline{B}^0$ decays, Δw_l, are determined using semileptonic and hadronic $b \to c$ decays [7, 10]. If $r \leq 0.1$, we set the wrong tag fraction to 0.5, and therefore the tagging information is not provided. The total effective tagging efficiency is determined to be 0.29 ± 0.01.

The vertex position for the f_{CP} decay is reconstructed using charged tracks that have enough SVD hits [16]. The $f_{\rm tag}$ vertex is obtained with well-reconstructed tracks that are not assigned to f_{CP}. A constraint on the interaction-region profile in the plane perpendicular to the beam axis is also used with the selected tracks.

Figures 1(a)-(m) show the distributions of reconstructed variables $\mathcal{R}_{\rm s/b}$, $M_{\rm bc}$ and p_B^* after flavor tagging and vertex reconstruction for $B^0 \to \eta' K^0$, ϕK^0 and $K_S^0K_S^0K_S^0$ candidates. The $M_{\rm bc}$ distribution for the $B^0 \to J/\psi K_S^0$ candidates and p_B^* distribution for the $B^0 \to J/\psi K_L^0$ candidates are shown in Fig. 2. The signal yield for each mode is obtained from an unbinned maximum-likelihood fit to these distributions; the ΔE distribution is also included in the fit for the modes without a K_L^0 meson. The signal shape for each decay mode

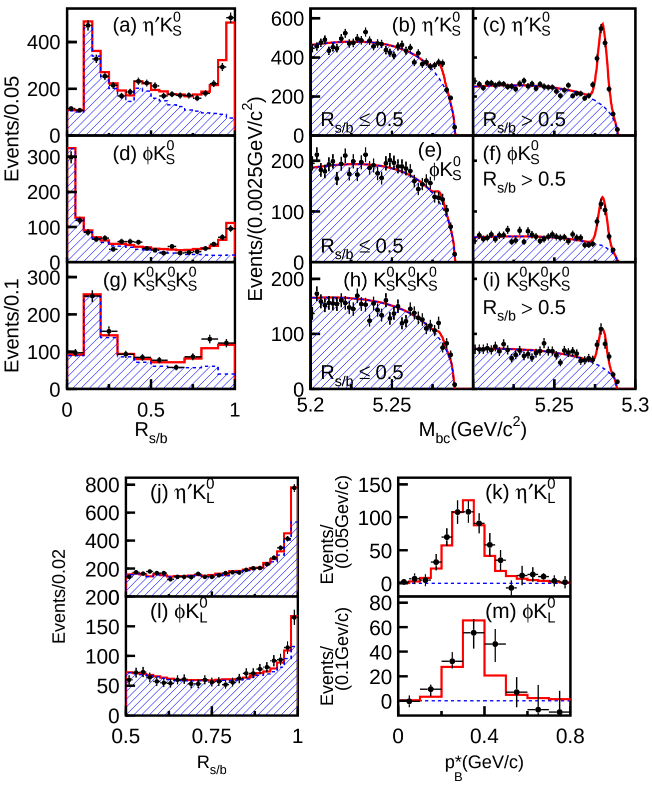

FIG. 1: $\mathcal{R}_{\rm s/b}$, $M_{\rm bc}$ and p^*_B distributions for reconstructed candidates: $\mathcal{R}_{\rm s/b}$, $M_{\rm bc}$ with $\mathcal{R}_{\rm s/b} \leq 0.5$ and $M_{\rm bc}$ with $\mathcal{R}_{\rm s/b} > 0.5$ distributions for (a, b and c) $B^0 \to \eta' K^0_S$, (d, e and f) $B^0 \to \phi K^0_S$, and (g, h and i) $B^0 \to K^0_S K^0_S K^0_S$; $\mathcal{R}_{\rm s/b}$ and p^*_B for (j and k) $B^0 \to \eta' K^0_L$ and (l and m) $B^0 \to \phi K^0_L$. The solid curves and histograms show the fits to signal plus background distributions, and hatched areas show the background contributions. Background contributions are subtracted in figures (k) and (m).

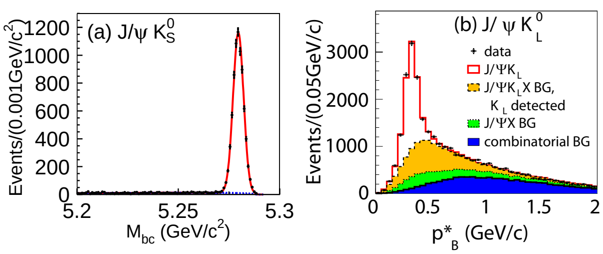

FIG. 2: (a) $M_{\rm bc}$ distribution in the ΔE signal region for selected $B^0 \to J/\psi K^0_S$ candidates and (b) p^*_B distribution for selected $B^0 \to J/\psi K^0_L$ candidates.

is determined from MC events. The background has two components: continuum, which is modeled using events outside the signal region, and $B\overline{B}$ background, which is modeled with MC events. The signal yields are determined to be 307 ± 21 for $B^0 \to \phi K^0_S$, 114 ± 17 for $B^0 \to \phi K^0_L$, 1421 ± 46 for $B^0 \to \eta' K^0_S$, 454 ± 39 for $B^0 \to \eta' K^0_L$, 185 ± 17 for $B^0 \to K^0_S K^0_S K^0_S$, 7484 ± 87 for $B^0 \to J/\psi K^0_S$ and 6512 ± 123 for $B^0 \to J/\psi K^0_L$, where errors are statistical only.

We determine $\mathcal{S}_f$ and $\mathcal{A}_f$ for each mode by performing an unbinned maximum-likelihood fit to the observed Δt distribution. The probability density function (PDF) for the signal distribution, $\mathcal{P}_{\rm sig}(\Delta t; \mathcal{S}_f, \mathcal{A}_f, q, w_l, \Delta w_l)$, is given by Eq. (1) fixing τ_{B^0} and Δm_d at their world average values [17] and incorporating the effect of incorrect flavor assignment. The distribution is convolved with the proper-time interval resolution function $R_{\rm sig}(\Delta t)$, which takes into account the finite vertex resolution [16]. We determine the following likelihood for each event:

$$P_i = (1 - f_{\rm ol}) \sum_k f_k \int [\mathcal{P}_k(\Delta t') R_k(\Delta t_i - \Delta t')]\, d(\Delta t') + f_{\rm ol} P_{\rm ol}(\Delta t_i), \quad (2)$$

where k denotes signal, continuum and $B\overline{B}$ background components. In the $B^0 \to K^0_S K^0_S K^0_S$ and $J/\psi K^0_S$ samples the $B\overline{B}$ component is negligibly small and not included in the fit. The fraction of each component f_k depends on the r region and is calculated on an event-by-event basis as a function of the following variables: ΔE and $M_{\rm bc}$ for $B^0 \to J/\psi K^0_S$; p^*_B for $B^0 \to J/\psi K^0_L$; p^*_B and $\mathcal{R}_{\rm s/b}$ for $B^0 \to \eta' K^0_L$ and ϕK^0_L; $M_{\rm bc}$ and $\mathcal{R}_{\rm s/b}$ for $B^0 \to \phi(\to K^0_S K^0_L) K^0_S$; ΔE, $M_{\rm bc}$ and $\mathcal{R}_{\rm s/b}$ for the other modes. The PDF $\mathcal{P}_k(\Delta t)$ for background events is convolved with the resolution function R_k for the background [7, 10]. The term $P_{\rm ol}(\Delta t)$ is a broad Gaussian function that represents a small outlier component with a fraction of $f_{\rm ol}$ [16]. The only free parameters in the fits are $\mathcal{S}_f$ and $\mathcal{A}_f$, which are determined by maximizing the likelihood function $L = \prod_i P_i(\Delta t_i; \mathcal{S}_f, \mathcal{A}_f)$ where the product is over all events.

Table I summarizes the fit results for $\sin 2\phi_1^{\rm eff}$ and $\mathcal{A}_f$. These results are consistent with and supersede our previous measurements [7, 10]. Fits to each individual mode

TABLE I: Results of the fits to the Δt distributions. The first errors are statistical and the second errors are systematic.

Mode	$\sin 2\phi_1^{\rm eff}$	$\mathcal{A}_f$
ϕK^0	$+0.50 \pm 0.21 \pm 0.06$	$+0.07 \pm 0.15 \pm 0.05$
$\eta' K^0$	$+0.64 \pm 0.10 \pm 0.04$	$-0.01 \pm 0.07 \pm 0.05$
$K^0_S K^0_S K^0_S$	$+0.30 \pm 0.32 \pm 0.08$	$+0.31 \pm 0.20 \pm 0.07$
$J/\psi K^0$	$+0.642 \pm 0.031 \pm 0.017$	$+0.018 \pm 0.021 \pm 0.014$

with K^0_S and K^0_L yield $(\mathcal{S}_{\eta' K^0_S}, \mathcal{A}_{\eta' K^0_S}) = (+0.67 \pm 0.11, -0.03 \pm 0.07)$, $(\mathcal{S}_{\eta' K^0_L}, \mathcal{A}_{\eta' K^0_L}) = (-0.46 \pm 0.24, +0.09 \pm 0.16)$, $(\mathcal{S}_{\phi K^0_S}, \mathcal{A}_{\phi K^0_S}) = (+0.50 \pm 0.23, +0.11 \pm 0.16)$, $(\mathcal{S}_{\phi K^0_L}, \mathcal{A}_{\phi K^0_L}) = (-0.46 \pm 0.56, -0.15 \pm 0.38)$, $(\mathcal{S}_{J/\psi K^0_S}, \mathcal{A}_{J/\psi K^0_S}) = (+0.643 \pm 0.038, -0.001 \pm 0.028)$ and $(\mathcal{S}_{J/\psi K^0_L}, \mathcal{A}_{J/\psi K^0_L}) = (-0.641 \pm 0.057, +0.045 \pm 0.033)$, where errors are statistical only. We define the background-subtracted asymmetry in each Δt bin by $(N_+ - N_-)/(N_+ + N_-)$, where N_+ (N_-) is the signal yield with $q = +1$ (-1). Figures 3(a)-(d) show the Δt distributions and asymmetries

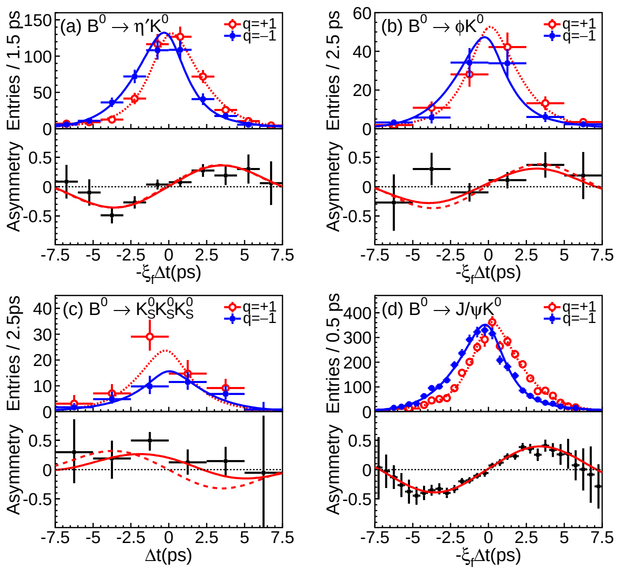

FIG. 3: Background subtracted Δt distributions and asymmetries for events with good tags ($r > 0.5$) for (a) $B^0 \to \eta' K^0$, (b) $B^0 \to \phi K^0$, (c) $B^0 \to K^0_S K^0_S K^0_S$ and (d) $B^0 \to J/\psi K^0$. In the asymmetry plots, solid curves show the fit results; dashed curves show the SM expectation from our $B^0 \to J/\psi K^0$ measurement.

for good tag quality ($r > 0.5$) events. The sign of each Δt measurement for final states with a K^0_L is inverted in order to combine results with K^0_S and K^0_L mesons.

The dominant sources of systematic error for $\sin 2\phi_1^{\rm eff}$ in $b \to s\bar{q}q$ modes come from the uncertainties in the resolution function for the signal (0.03 for the $B^0 \to \eta' K^0$ mode, 0.04 for the ϕK^0 mode, 0.05 for the $B^0 \to K^0_S K^0_S K^0_S$ mode) and in the background fraction (0.02, 0.04, 0.06). The effect of $f_0(980)K^0$ background in the ϕK^0 mode (0.02) is estimated using the BES measurement of the $f_0(980)$ lineshape [18] and is included in the background fraction systematic error. The dominant sources for $\mathcal{A}_f$ in $b \to s\bar{q}q$ modes are the effects of tag-side interference [19] (0.02, 0.03, 0.04), the uncertainties in the background fraction (0.02, 0.03, 0.05), in the vertex reconstruction (0.02 for all modes) and in the resolution function (0.02, 0.01, 0.02). We study the possible correlations between $\mathcal{R}_{\rm s/b}$, p_B^* and r PDFs used for ϕK^0_L and $\eta' K^0_L$, which are neglected in the nominal result, and include their effect in the systematic uncertainties in the background fraction. Other contributions come from uncertainties in wrong tag fractions, the background Δt distribution, τ_{B^0} and Δm_d. A possible fit bias is examined by fitting a large number of MC events and is found to be small.

The dominant sources of systematic errors for the $B^0 \to J/\psi K^0$ mode are the uncertainties in the vertex reconstruction (0.012 for $\sin 2\phi_1$, 0.009 for $\mathcal{A}_f$), in the resolution function for the signal (0.006, 0.001), in the background fraction (0.006, 0.002), in the flavor tagging (0.004, 0.003), a possible fit bias (0.007, 0.004) and the effect of the tag-side interference (0.001, 0.009). Other contributions amount to less than 0.001. We add each contribution in quadrature to obtain the total systematic uncertainty.

For the $B^0 \to \eta' K^0$ mode, we observe CP violation with a significance equivalent to 5.6 standard deviations for a Gaussian error, where the significance is calculated using the Feldman-Cousins frequentist approach [20]. The results for $B^0 \to \eta' K^0$, ϕK^0 and $K^0_S K^0_S K^0_S$ decays are all consistent with the value of $\sin 2\phi_1$ obtained from the decay $B^0 \to J/\psi K^0$ within two standard deviations. No direct CP violation is observed in these decay modes. Further measurements with much larger data samples are required to search for new, beyond the SM, CP-violating phases in the $b \to s$ transition.

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